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LIMITS FOR ACCEPTABLE USE OF WORN RAILS ON UK STANDARD GAUGE HERITAGE RAILWAYS

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ABSTRACT

In 2011, UK heritage railways carried 7.1 million passengers on over 530 miles of track, accounting for £92 million of direct revenue. Much of this operation uses steam locomotives with relatively high axle loads and reciprocating motion which can lead to uneven track loading. However the majority of track components on heritage lines are antiquated due to reliance on cascaded components and in some cases on the deliberate retention of chaired bullhead rail for conservational purposes.

This research provides an assessment of current methodologies regarding the management of steel rails on heritage railways: the measurement of rail wear, the assessment of the residual strength in worn rails and the subsequent determination of a rail's critical wear limit. It describes the effectiveness and adequacy of some of the inspection regimes in use and addresses the risks associated with the variation in these regimes across the sector.

A survey of permanent way supervisors on UK standard gauge heritage lines is reported and the permanent way in use is and the perceived requirements for its renewal are summarised. Due to low speeds and traffic levels, the main line standards for rail wear are generally thought to be inappropriate for heritage railway use whilst 'high-tech' methods for measuring crack propagation and rail wear are inaccessible due to cost. A common approach is to employ inspection and maintenance regimes developed by British Rail for use on rural lines.

Utilising a fracture mechanics approach to predicting rail failure developed in the USA, the research highlights a more relevant set of guidelines, providing a matrix detailing acceptable wear limits based on inspection frequency, rail type, formation condition and traffic levels.

The findings will benefit the heritage rail industry by minimising risk whilst accounting for resource limitations.

INTRODUCTION AND BACKGROUND

Across the UK there are over 100 operating heritage railways (HRs), running a huge variety of rolling stock on over 530 miles of track. In 2011 this industry accounted for £92 million of the UK's tourist revenue and carried over 7 million passengers on lines across the country. The lines are operated by as many as 2200 permanent staff and 18500 volunteers (Lord Faulkner 2011) with a wide range of expertise and an extensive if unconsolidated knowledge base, with years of experience.

As with their locomotives and rolling-stock, HR track is often old. Many lines deliberately set out to use jointed, chaired bullhead rails (BH), typically of 95 lb/yard section, to maintain a 'steam-age' atmosphere, at least in their stations, and since new supplies of BH are difficult to obtain in moderate quantities at a reasonable price, use is made of recycled rails and components cascaded from mainline or other non-heritage sources, with these having already experienced loss of cross section due to wear. This worn material is then retained in service for longer periods than might be the case on the mainline network before renewal. HRs also operate with restricted resources, and for this reason are keen to use donated or cheaply bought worn and recycled track components where possible.

This situation presents a management issue for HRs, which generally operate at considerably slower line speeds and reduced annual tonnages of traffic compared with the mainline, but often employ historic steam locomotives with relatively high axle loadings and reciprocating motion that can be difficult to balance perfectly. Nevertheless, UK HRs are subject to the same requirement to ensure the safety of passengers, staff and third parties as mainline railway companies, with operational safety being overseen by the Office of Rail Regulation (ORR). Of particular concern to the ORR is the requirement to determine whether given recycled rail components are safe for traffic if they exhibit considerable signs of wear.

This paper examines the use of worn rails on UK HRs from the perspective of both HR management and regulators and sets out to establish a scientific basis for defining limits of wear for acceptable use of worn, recycled rails in an HR context.

EXISTING STANDARDS AND HR MANAGEMENT PRACTICES

Limits for head height loss and gauge-face width loss due to wear in the mainline context are derived from the Railway Group Standards (RGS) (Railway Group Standards 2011). In this standard, the maximum allowable head wear on 95lb BH varies with dynamic axle loading. Assuming a dynamic axle loading of 30 tons (corresponding to a 22.5 ton static axle loading typical of many larger steam locomotives) the standard permits rail head height loss of just over 5mm before renewal, this being less than a 7% reduction in rail cross sectional area. At the other extreme, the maximum head wear before flange strikes on fishplates become inevitable is 14.8mm for 95 lb BH. This is just under a 20% reduction in rail cross sectional area. For side wear, the RGS limit is 9 mm off either face, or a minimum width of 52mm.

The authors carried out a telephone survey of HR permanent way managers during 2012-2013. This remains on-going, but so far 20 of the 70 standard gauge heritage lines have been questioned, covering a total of 187 miles of running line, 45% of the total of UK standard gauge HR running line. It was found that 69% of this was laid in BH with 31% in flat-bottomed rail (FB), all of it on a variety of ages and types of sleeper and fastening and sourced from a variety of places including British Rail (BR) and former power stations or industrial sites. The most common BH section was 95 lb/yard except on former Great Western Railway lines where it was 97.5 lb/yard. The oldest rail still in traffic dated from 1918 with rails from the 1920s and 1930s being very common.

Traffic levels ranged from 17 trains/day down to 2 trains/day or less, with static axle loads of 22.5 to 25 tons being common.

Most lines surveyed tended to operate weekly line walks during their running season with less frequent supervisor or civil engineer inspections and only occasional technological monitoring such as geometry

measurement. 'High tech' inspections such as use of Track Recording Vehicles or ultrasound surveys of rail materials were rare and typically only carried out where these were available at no or reduced cost due to local arrangements with mainline companies.

In terms of maintenance intervention standards, a wear rate of 1 mm of head height loss per ten years in use was commonly quoted. This has previously been adopted by engineers on some rural mainlines such as those in northern Scotland (Hill-Smith 1989). It was common for RGS wear limit figures to be known, but equally a common rule of thumb was "at or slightly above the bottom of the side" for gauge-face side wear. Head wear, on the other hand, had no identifiable common approach, with some lines rigorously applying RGS standards and others stating that indications of fishplate flange strikes were the point at which head wear was addressed.

In general, rail wear was not considered a threat to services, with a total of only 22 rail break incidents in the last ten years, affecting only six HR passenger services. It was noted that rail breaks were often associated with a particular batch of rails, suggesting material issues rather than just long use. Bolt hole failures were more common, but the biggest threat to safety was regarded as in-gauge track misalignment due to buckling and excessive cant gradient.

It was felt that there was sometimes insufficient clarity from the ORR regarding operating standards, with HRs being expected to maintain track standards such as Network Rail or RGS standards. There was also frustration at 'buying blind', with better records for rails being needed to identify the remaining life in recycled rails and to isolate poor batches of rail.

On the other hand, discussions with the ORR indicate that their difficulty is the lack of scientific foundation on which to assess the safety of worn, recycled rails. Combined with the hugely varying nature of HR track and the wide variety of management practices discussed above, this leads to a highly unsatisfactory situation in ensuring the safety of the HR sector.

RISK DUE TO RAIL FAILURE

Rail defects have, in fact, accounted for a series of incidents on the UK mainline network, the most serious recent event being the Hatfield incident of 2000, in which four people were killed due to a rail break resulting from rolling contact fatigue (Office of Rail Regulation 2006). The most fatalities in a single rail-defect related incident occurred at Hither Green in 1967 when 49 people died in a derailment caused by bolt-hole cracking (McMullen 1968).

Both these incidents occurred at speeds of 70 mph or more on the mainline network. Whilst there have been no serious incidents related to rail defects on UK HRs, there have been incidents at low speeds on the mainline network arising from causes which could have occurred on HRs. Table 1 summarises such incidents reported between 1900 and 2012, noting the number that occurred at speeds of 30mph or less, corresponding roughly to HR operating conditions.

The highest number of incidents at sub-30mph speeds correspond to switch and crossing (S&C) issues and track geometry faults, but mid-section rail failure and flange climb on worn rail profiles, both of which depend on the amount and type of rail wear, account for nine derailments out of a total of fourteen such incidents at all speeds.

The risk of derailment due to the use of recycled track components under HR-like operating conditions cannot therefore be said to be zero.

Table 1: Significant UK derailments from track defects (1900-2012)
(sourced from The Railways Archive: www.railwaysarchive.co.uk)

Incident Type	Total Number	Number at speeds of 30mph or less
Failure of switch and crossing (S&C) components	23	15
Gauge widening from track system failure (chair/sleeper/substrate)	25	14
In-gauge track misalignment (eg buckle)	53	14
Poor curve layout (eg excessive cant gradient)	15	9
Mid-section rail failure	12	7
Overloaded track system	4	2
Flange climb on worn rail profile	2	2
Bolt-hole failure	11	0
Welded joint failure	2	0
Total Incidents	147	63

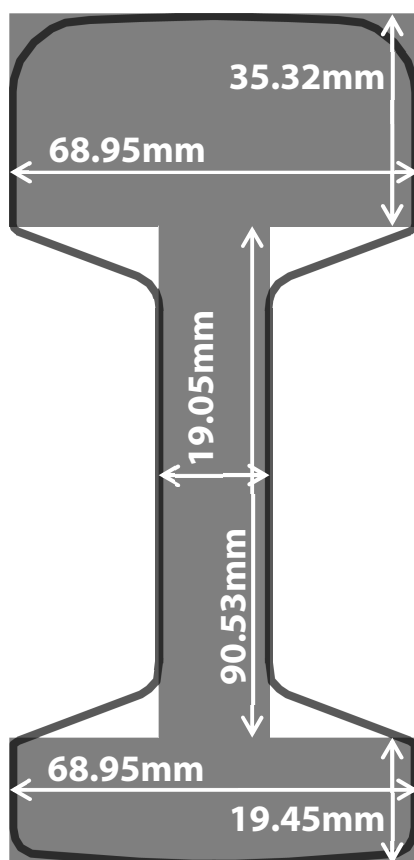


Figure 1: 95 lb/yd bullhead rail showing simplified geometry

SCIENTIFIC ASSESSMENT OF RAIL STRENGTH

Bending stresses

One approach to developing a scientific assessment of the strength of rails is simply to consider them as a beam. In 1867, Winkler proposed that a rail could be satisfactorily modelled as a beam on an elastic foundation (Barati and Sadeghi 2010). In order to apply this approach, a 95 lb BH was assumed to be a simple I-beam with dimensions as shown in white in Figure 1. This assumption fractionally increases the quantity of material at the extreme fibres of the cross-section, leading to a 7% overestimation of the total cross sectional area and a second moment of area of 1419cm^4 as opposed to the 1458cm^4 quoted for 95 lb BH in BS11:1985. This discrepancy was considered to be negligible for the purposes of this analysis.

Analysing the rail as a linear elastic Euler beam (as detailed by both (Jeong 2003) and (Hunt 2005)) and using a yield stress for rail steel of 406Nmm^{-2} (Ringsberg, Loo-Moorey et al. 2000), a factor of safety can then be found comparing the imposed bending moment from traffic loading with the required moment for the rail to fail. This was done for a range of wear values and an assumed vertical loading of 300 kN (corresponding approximately to a 30 ton dynamic axle loading as discussed above). The factors of safety were found to be between 6 and 9, as shown in Table 2. This implies that full section yield would not occur in pure bending, even with over a 40% reduction in rail head cross-sectional area.

Table 2: Factors of safety calculated from bending moment considerations

Head height loss Δh (mm)	Vertical second moment of area I_{yy} (cm^4)	Safety factor for elastic bending γ_e	Safety factor for full section yield γ_p
0	1418.5	7.6	8.9
4	1297.7	7.2	8.5
8	1178.8	6.7	8.2
12	1061.2	6.2	7.8
16	944.1	5.7	7.3
20	826.8	5.1	6.8

Fracture mechanics

The bending stress approach is, intuitively, unrealistically un-conservative: rails are not for practical purposes that strong. An alternative approach is that of fracture mechanics, which was initially developed within the aeronautical industry, and several methodologies have been investigated for use in the rail industry (Rail Safety and Standards Board 2006). Its use has been expanded in research on behalf of the American Railway Engineering and Maintenance-of-Way Association (AREMA) and the International Union of Railways (UIC) (Lyons, Jeong et al. 2010) and included some observation of low speed, high axle load rail vehicles in the form of freight traffic in the USA. It is this analysis methodology that has been pursued here.

Fracture mechanics assumes that a rail cross section has an inherent detail flaw in the rail head area and finds stress intensity factors from both the residual stress in the rail from the fracture and the bending stress resulting from the traffic loading. In tests conducted in both laboratory conditions and through samples taken from running lines, these detail flaws were found to be detectable when their cross-sectional area was greater than 5% of the rail head area, and in most cases led to rail failure when they reached a size greater than 50% of the rail head area (Jeong 2003).

Flaws manifest themselves as tache ovals in rail sections and as transverse cracks (Kumar 2006). Tache oval defects were common on the British mainline until the 1980s when improvements in both steel manufacturing and inspection techniques largely eliminated them as a problem (Rail Safety and Standards Board 2006). Until this, however, such cracks represented over 15% of recorded rail failures (Tunna 1989), so it is reasonable to assume that they are present in a significant number of recycled, worn rails in operation on HRs.

The fracture analysis on which this work is based (Lyons, Jeong et al. 2010) focuses on US and UIC 60 FB sections, but here it has been applied to BH, since this rail profile is the most degraded in operation on many UK HRs. A schematic representation of a tache oval fracture in a BH rail section is included in Figure 2.

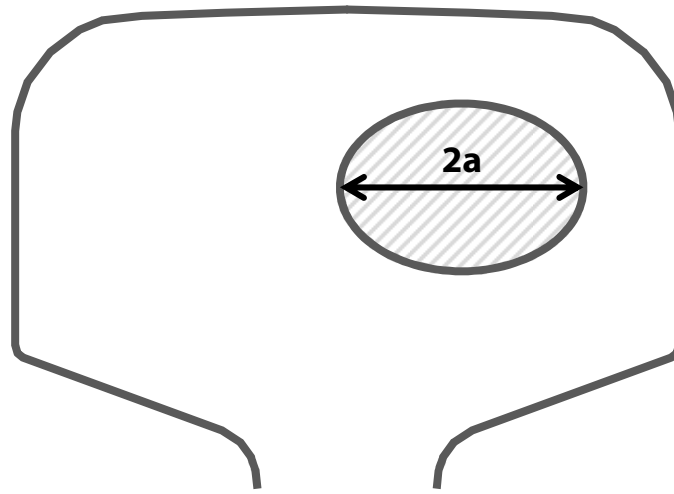


Figure 2: Schematic representation of tache oval fracture in bullhead rail head

(Lyons, Jeong et al. 2010)'s method depends on calculating a stress intensity factor K_i which can be compared with the toughness of the rail material. K_i is defined by

$$K_i = \frac{2}{\pi} \alpha_s \alpha_c (\sigma_R + \alpha_g \sigma_B) \sqrt{\pi a} \quad (1)$$

where σ_R is the residual stress due to the fracture, σ_B is the bending stress due to loading, a is the horizontal fracture radius and α_s , α_c and α_g are magnification factors due to the shape of the fracture, its interaction with the surface of the rail head and the stress in laterally loaded track.

An assumed value for the fracture horizontal radius a is used leading to a ratio A_f/A_H describing the area of the fracture divided by the total area of the rail head, allowing for any reduction in rail head area due to either head or gauge-face side wear. In the present work, α_s is then taken as 0.984, corresponding to an elliptical fracture with a height to width ratio of 0.7 and α_c is determined from

$$\alpha_c = \sqrt{\frac{2}{\pi \frac{A_f}{A_H}} \tan\left(\frac{\pi A_f}{2 A_H}\right)} \times \left(\frac{0.63 + 2.02 \frac{A_f}{A_H} + 0.37 \left[1 - \sin\left(\frac{\pi A_f}{2 A_H}\right)\right]^3}{\cos\left(\frac{\pi A_f}{2 A_H}\right)} \right) \quad (2)$$

For simplicity, our analysis is limited to straight plain line, and α_g is therefore assumed to be unity.

The residual stress in the rail, σ_R , is then determined following (Clayton and Tang 1992):

$$\sigma_R = \begin{cases} 206.9 - 14.65 \left(\frac{A_f}{A_H} \times 100 \right) & 0 \leq \frac{A_f}{A_H} \leq 0.1 \\ 68.95 - 0.86 \left(\frac{A_f}{A_H} \times 100 \right) & \frac{A_f}{A_H} > 0.1 \end{cases} \quad (3)$$

The numbers in equation (3) are empirical factors. It should be noted that the value 68.95 in the second line of the right hand side of this equation is unrelated to the rail head width of 68.95 mm of BS11-95R BH.

σ_B is determined from loading, considering an elastic foundation representative of sleepers, ballasted track, as fully explained in (Jeong, Tang et al. 1998). In our case lateral loading was neglected since the analysis was for straight track.

The original analysis was developed for continuous welded rail (CWR) and also includes a thermal stress component σ_T . However in this work we are assuming jointed track as is typical for BH on HRs, and have therefore assumed σ_T to be zero.

RESULTS

The analysis described above was carried out for the simplified 95 lb/yd BH section shown in Figure 1, a 300 kN vertical load and a range of rail wear and fracture sizes as set out in Table 3. The resulting K_i values are plotted in Figure 3 and **Error! Reference source not found.** For rail steel with a toughness of $30 \text{ Nmm}^{-2} \text{m}^{0.5}$ (Yates 1996) (shown on the figures by a broad chain line) this gives a matrix of acceptable fracture sizes and rail wear as shown in Table 4.

Table 3: Detail fracture sizes and rail wear used in calculations

Head height loss calculation		Gauge-face width loss calculation	
Detail fracture sizes a (mm)	Rail height loss (head wear) (mm)	Detail fracture sizes a (mm)	Gauge-face width loss (side wear) (mm)
16	0	20.0	0
17	4	20.5	4
18	8	21.0	8
19	12	21.5	12
20	16	22.0	16
	20		20

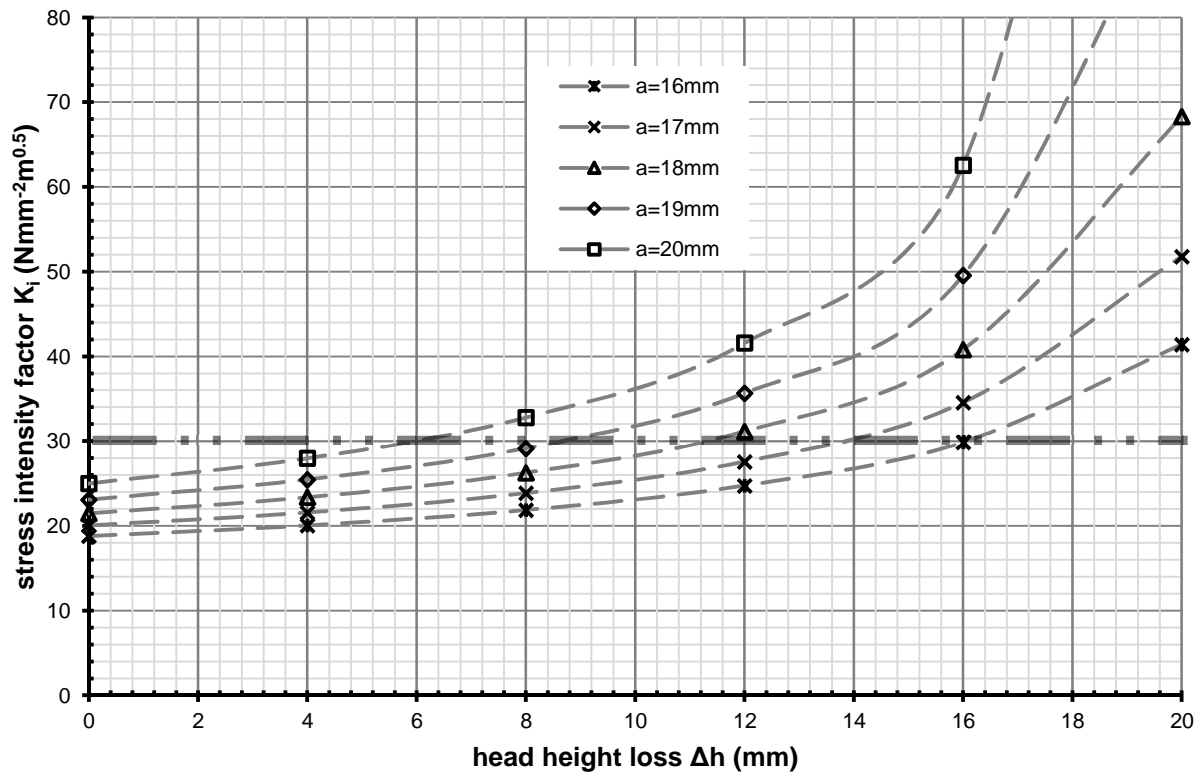


Figure 3: Results showing stress intensity factor against head height loss for various detail fracture sizes

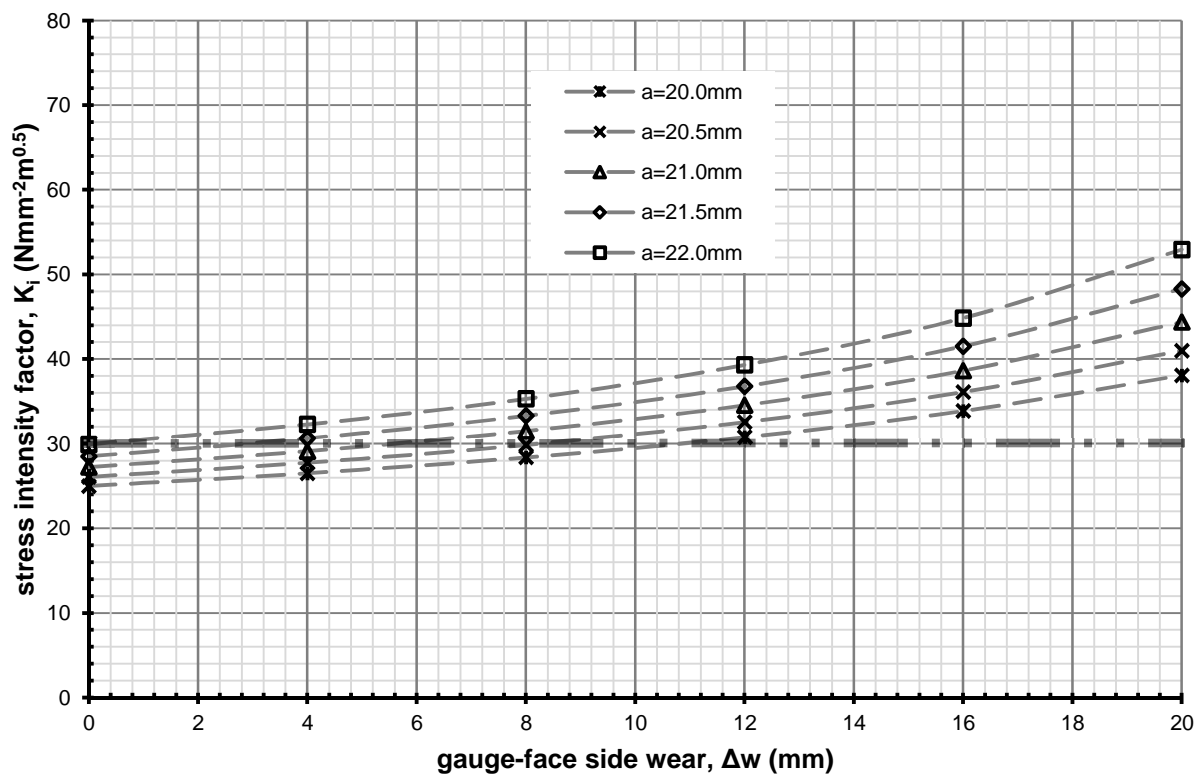


Figure 4: Results showing stress intensity factor against gauge-face width loss for various detail fracture sizes

Table 4: Matrix of acceptable wear levels against detail fracture sizes for head height loss and gauge-face width loss

Head height loss (head wear)		Gauge-face width loss (side wear)	
horizontal fracture radius a (mm)	critical depth reduction Δh (mm)	horizontal fracture radius a (mm)	critical width reduction Δw (mm)
16	16.06	20.0	10.85
17	13.72	20.5	8.26
18	11.26	21.0	5.62
19	8.66	21.5	2.93
20	5.94	22.0	0.19

DISCUSSION

It should be emphasized that for 95 lb BH in jointed track, there is an absolute head wear limit of 14.8 mm before flange strikes on fishplates will start to occur. Wear will also increase the tendency for derailment due to gauge widening and flange-climb, which may well be much more critical than rail failure and are not addressed in the foregoing analysis. Similarly, wear on S&C components is likely to have a critical impact well before structural failure of the rail is imminent. The results of Table 4 must therefore be viewed in this context.

It should also be noted that this analysis is not conservative in that it does not consider curved track, where lateral loading will reduce acceptable wear for a given detail fracture size, or CWR or other track where thermal stresses may be significant (including jointed track where the fishplates have not been properly lubricated). Only a single loading has been considered, which will not be appropriate for all HRs, and further investigation is necessary to prove that the analysis can be applied as it stands to BH rail, for which it was not originally developed. Finally, the simplified geometry of Figure 1 will have a marginal effect on the results compared with the actual geometry and this should also be checked.

It can however be seen from the results that for detail fracture sizes in the range examined, and for a 300 kN loading on straight plain line, critical head wear in the range of around six to 14 mm and critical side wear ranging from 0.2 for very large detail fractures up to 11 mm is possible before rail failure. This suggests that structural failure of rails will be restricted to severe and relatively rare conditions, even for quite worn rail (whilst the other derailment factors such as track geometry will remain significant).

In order to complete this analysis it is, however, essential to have a realistic view of the detail fracture sizes likely to be present in HR rails. The original analysis of (Jeong, Tang et al. 1998) addressed this by looking at fracture development in rails as a function of lifetime traffic, considering rails laid new and worn in a single usage situation.

On UK HRs, the use of rails is very different from this: they are typically pre-worn when sourced and may already have been used in several locations and subject to several different traffic patterns and loadings. The kind of analysis undertaken by (Jeong, Tang et al. 1998) is therefore impossible in this context. There is also the issue of potentially flawed batches of rail which arose in the telephone survey of HR permanent way managers discussed above.

The only meaningful way forward would be to undertake a programme of testing of rails in use, or being considered for use, on HRs and determine the number and size distribution of fractures likely to be present. This is a subject for future research.

Also a subject for future research specific to the HR context is the appropriate tolerance for gauge, cant gradient, S&C and other alignment issues in low speed, low tonnage and high axle load situations. A great deal of literature exists on wheel-rail interaction generally, and it would be helpful to review this in a structured way from the HR operation perspective.

In the meantime the foregoing analysis suggests that from the point of view of HR management and regulators, the structural integrity of the rails is likely to be of relatively limited significance in the safe operation of HRs when compared with derailment risks due to other causes such as buckling, excessive cant gradient and wear effects on gauge and on S&C, which can usually be addressed by maintenance not involving significant rail replacement. This implies that recycled rails, even when considerably worn, will often be safely usable provided that track geometry is properly maintained, with consequent useful implications for the limited resources of HR management.

CONCLUSIONS

The use of worn rails on UK HRs has been examined from the perspective of both HR management and regulators.

A telephone survey of permanent way managers showed that a significant mileage of BH remains in use, with many rails being 80-100 years old. Traffic was always less than 17 trains/day and rail wear was not thought to be a problem with the number of rail break incidents being low and sometimes linked to poor batches of material. Renewal practices varied but in terms of head height loss were often linked to incipient flange strikes on fishplates.

A fracture mechanics approach developed in the USA was applied to determine the strength of rails under a 300 kN load corresponding roughly to a heavy steam locomotive, assuming 95 lb/yd BH on straight plain line. It was found that for detail fracture sizes ranging from 15 to 22mm, safe head wear was in the range 14 mm down to 6 mm and safe side wear ranged from 11 mm to 0.2 mm. Fracture sizes are however assumed, and further work is needed to identify typical values in HR rails.

These limits are for the structural integrity of the rail only: other wear-related derailment risks such as gauge widening due to side wear, increased risk of flange climb and defects in S&C components were not included in the analysis and further work is needed to quantify these in a specifically HR context.

The findings indicate that in the overall context of the safety of UK HR operations, structural failure of recycled rails due to wear is not likely to be significant compared with other risks to track geometry and alignment, which can often be addressed without rail replacement.

This finding will provide some assistance to regulators in assessing the safety of HR permanent way and has useful implications for the limited resources of HR management.

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